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Abstract

Passive control of shear flow is used to control the rate of mixing and stability of submerged gaseous jets in liquids. The object is to evaluate the effectiveness of recently developed shear flow control techniques for application to gaseous jets injected into liquids and ultimately to apply these techniques to gaseous oxidants injected into liquid metal fuels. These control techniques have been initially tested in non-reacting gas/liquid systems. A large increase in degree of mixing and jet stability occurs when non-axisymmetric nozzles are used as injectors relative to injection by axisymmetric Fanno tube type nozzles. Jet volume spreading rate is increased by a factor of 4. A characteristic instability (the "reverse shock" or "reverse flow" effect) occurring in such two-phase systems is greatly reduced by passive control of the shear flow. A simple passive technique of controlling entrainment is described which is effective in eliminating the reverse flow effect. The relevance of these control techniques to liquid metal combustion is discussed.

I. Introduction.

The injection of gas oxidant jets into liquid metal fuels is characteristic of power systems under development for propulsion of underwater vehicles. Previous work has identified a number of combustion instabilities and inefficiencies[1-5] which may be improved or eliminated by applying passive or active control techniques to injection of the gaseous oxidant into the liquid metal fuel. Simple passive control techniques are demonstrated which increase mixing and reduce instability in submerged gaseous jets in liquids.

Control of the shear flow in reacting and non-reacting single phase systems (gas/gas) and in non-reacting liquid/liquid systems has been demonstrated by Schadow et al.[6-10] at the Naval Air Warfare Center (NAWC). The researchers at NAWC showed that changes in shear flow produced by altering the nozzle geometry significantly change the jet size, shape and mixing characteristics.

The object of this work is to demonstrate shear flow control in a two-phase system and ultimately to apply these techniques in liquid metal combustion systems and to evaluate their potential to improve the liquid metal combustion process.

II. Liquid Metal Combustion.

The typical reaction used in liquid metal combustion is

$$8Li + SF_6 \rightarrow Li_2 + 6LiF$$

Sulfur hexafluoride gas is injected under choked conditions into liquid lithium. The gas dissociates and reacts as it mixes with the metal fuel. The relevant features of this reaction for marine propulsion are the large amount of heat released and the reaction products are more dense than the fuel, allowing the reaction to proceed in a closed system, i.e. there is no need for an exhaust.

Parnell et al.[1-4] have used X-radiography to obtain images of the liquid metal combustion process. Fig. 1 shows a schematic diagram of a typical liquid metal combustor used for X-radiographic studies. The combustion chamber contains lithium metal and a small amount of start charge (aluminum perchlorate). The start charge is ignited electrically, melting the lithium, and sulfur hexafluoride is injected into the liquid metal bath under choked conditions (sonic

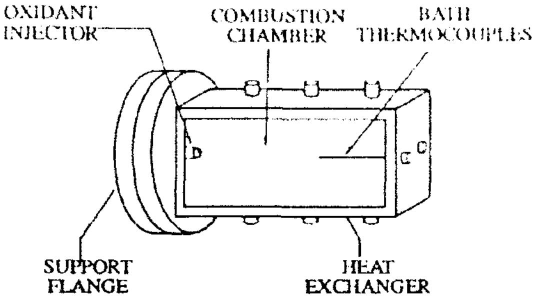

Figure 1. Schematic diagram of a liquid metal combustor.

velocity at the injector exit). The containment walls of the combustor are stainless steel.

Instabilities have been observed in liquid metal combustion which are related to mixing, circulation and sudden entrainment of liquid metal into the gas jet. Due to containment requirements, the walls of the combustor are made of a heat- and corrosion-resistant material such as stainless steel. The relative impermeability of such a material to X-radiation greatly reduces the image contrast which can be obtained. However it has been possible to obtain information by use of X-radiography as well as the use of sacrificial probes placed in the reaction zones. Estimates of the size and shape of the jet as well as the circulation patterns of the fuel and product and the location of reaction zones have been obtained.

Parnell found that the structure of the jet in liquid metal combustion normally consists of two parts. A relatively narrow ($3\text{-}4d_0$ in width), intensely reacting central region of flame, the length of which is in the range

$$25 < \frac{l_f}{d_0} < 50 ,$$

where l_f is the flame length and d_0 is the nozzle exit diameter. This core region has high velocity and is relatively unaffected by buoyant forces. External to the core is a broad plume (about $25d_0$ wide) which has much lower velocity and is visibly affected by buoyant forces. The length of the plume is

$$40 < \frac{l_p}{d_0} < 70 ,$$

where l_p is the plume length. Evidently, the core region is unmixed oxidant, while the external plume is a gas/liquid mixture of reaction products, fuel and oxidant.

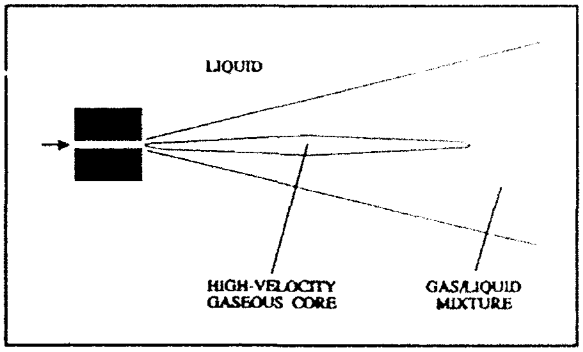

Figure 2. Diagram of a non-condensing jet. Arrow indicates gas flow direction.

The shape and penetration of the submerged jet are similar to those dimensions of a non-condensing, non-reacting jet in a liquid. A simplified schematic of the structure of a submerged gaseous jet in liquid is shown in Fig. 2. Loth and Faeth[11] showed that, when air is injected into water under choked conditions, there is a narrow high pressure core region where the time averaged void fraction is 1.0. The length of this region is $50\text{-}100d_0$, of the same order of magnitude as the core of the reacting jet in liquid metal combustion. External to this region is a gas/liquid mixing layer which has much lower velocity due to the large density of the liquid relative to the gas. Mixing of the much denser liquid with the gas causes a large decrease in velocity compared to the core region which is essentially unmixed gas. Due to the similarities between non-condensing, non-reacting jets and the reacting jet characteristics of liquid metal combustion, submerged nitrogen jets in water are used here to demonstrate control techniques for application to liquid metal combustion, although tests are also performed with steam injected into water for comparison to a rapidly condensing system.

Several types of instabilities have been observed in the liquid metal combustion system. First, the jet is very unstable and pulsative. This is probably caused by nonuniform or unstable entrainment of fuel into the jet. The instability of the jet may cause exposure of the containment materials to corrosive or combusting materials, ultimately resulting in containment failure. An improvement in mixing or modification of the entrainment characteristics of the jet will likely attenuate this instability.

Another type of phenomenon which occurs in liquid metal combustion is stratification of the fuel and much denser reaction products, caused by insufficient circulation in the bath. The reaction products of lithium and sulfur hexafluoride reaction are 3-5 times as dense as lithium metal and immiscible with molten lithium. If the fuel/reaction product mixture is not highly turbulent and well-stirred, the reaction products settle to the bottom of the container.

As a consequence of fuel/product stratification an effect called "surface combustion" occurs. This phenomenon occurs when stratification of the fuel/product mixture progresses to the point that combustion no longer takes place near the injector. A large amount of oxidant breaks out of the bath and the principal reaction zone is at the surface of the bath. This is not the ideal situation from the point of view of extracting thermal energy from the bath, and it can cause an anomalous region of high temperature to occur due to the low heat transfer occurring in the lower stratum of reaction products. This effect exposes the containment materials to hot corrosion, potentially breaching the containment vessel. The effect occurs at higher fuel utilizations and at reduced oxidant injection rates. An improvement in mixing will help maintain a large degree of turbulence in the bath which will help delay stratification and surface combustion.

III. Approach.

Due to the containment requirements and the hazardous nature of the liquid metal combustion process it is highly desirable to test these shear flow techniques in a non-reacting system before implementation in a liquid metal combustion reactor. Nitrogen injected into water is used as a non-condensing system and steam injected into water as a rapidly condensing system. For reasons previously given, nitrogen injected into water is considered to be a more accurate model of the liquid metal combustion system.

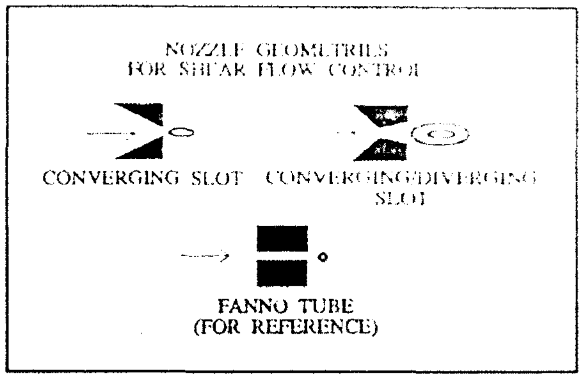

Figure 3. Three nozzle geometry types used for shear flow control of submerged gaseous jets. Arrows indicate gas flow direction and ellipses/circle indicate passage shape.

Test nozzles were machined from brass in geometries expected to generate large differences in shear flow structure. Fig. 3 shows cross-sectional schematic diagrams of three major nozzle types studied. These nozzle types are the same as some of those studied for gas/gas systems by the researchers at NAWC. The hydraulic diameter is held constant in comparisons between nozzle types. The hydraulic diameter chosen for demonstration purposes is 2.5mm. Gas is injected into water under choked conditions using the three types of nozzles shown in Fig 3. The pressure is recorded and mass flow rate measured with a Micro Motion Model D mass flow meter.

The resultant jets are illuminated with a stroboscopic lamp with a pulse width of 6 microseconds. The strobe is triggered from the vertical sync signal striped from the output video signal of a CCD camera. The vertical sync signal is reduced in frequency by a factor of 2 to obtain a 30 Hz trigger for the strobe. The strobed video images are recorded on super VHS format or professional format video recorders. The recorded images are later input for processing to a Megavision 1024 real-time image processor and individual frames can be stored in digital format for further processing or for printing.

Measurement of jet spreading rate was performed

Figure 4. Fanno tube injection of Nitrogen into water. Hydraulic diameter is 2.5 mm.

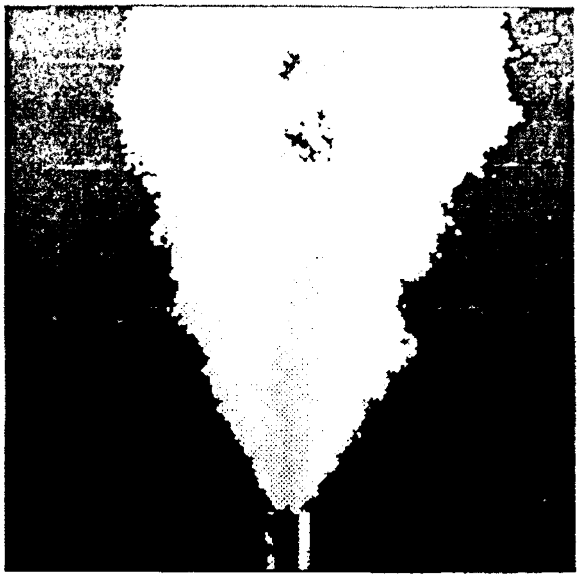

Figure 5. Injection of nitrogen into water with converging/diverging 3:1 slot nozzle. Spreading viewed in major axis. Hydraulic diameter is 2.5 mm.

by using the image processor to "grab" a series of video frames of the nozzles in operation at the specified parameters. The jet spreading angle is measured from the nozzle exit for a group of frames (seven) and the average taken. Video frames containing the image of a large scale disturbance (reverse flow) characteristic of submerged gaseous jets in liquids were discarded, the spreading angle measurement was made when the jet is in a "pure jet" mode.

IV. Jet Spreading.

Shown in Figs. 4,5 and 6 are Nitrogen jets injected into water. The jet in Fig. 4 is produced by a Fanno tube of hydraulic diameter 2.5 mm and mass flow 0.41 Kg/min. Jets in Figs. 5 and 6 are generated with a converging/diverging slot nozzle the hydraulic area and flow rate are the same as the previous figure, 2.5 mm and 0.41 Kg/min respectively. The converging section has a 40° half angle. There is a 3 to 1 aspect ratio at the throat and a 2 to 1 aspect ratio at the exit. The area ratio of throat to exit is 0.27 and the diverging section length is 3.8 mm.

The important differences in the jets produced by these two types of nozzles are; the large difference in spreading rate and the stability of the jet produced by the converging/diverging nozzle compared with the jet produced by the Fanno tube. The jet produced by the converging/diverging nozzle is divided into two secondary jets as compared to the single jet produced by the Fanno tube. This corresponds to the type of structure observed by Gutmark[6] et al. when injecting gas jets into gas with a converging slot nozzle. This dual jet structure was not pronounced when injecting gas into water with a converging slot nozzle as was seen by Gutmark, but only when the nozzle had a diverging section in addition to the converging section. This is likely due to the tendency of the much greater density of the liquid to inhibit development of the flow. When the nozzle has a diverging section this allows the flow pattern to develop in structure before it enters the liquid, allowing a flow pattern to develop which is much more similar to that occurring in gas/gas systems. The dual jet structure is also seen in a rapidly condensing system (steam injected into water) with a converging/diverging slot nozzle.

The jet in Fig. 6 is a view of the minor axis of the converging/diverging elliptical nozzle. The volume spreading rate is less than that in the major axis plane but still considerably greater than the volume spreading rate of a jet produced by a Fanno tube.

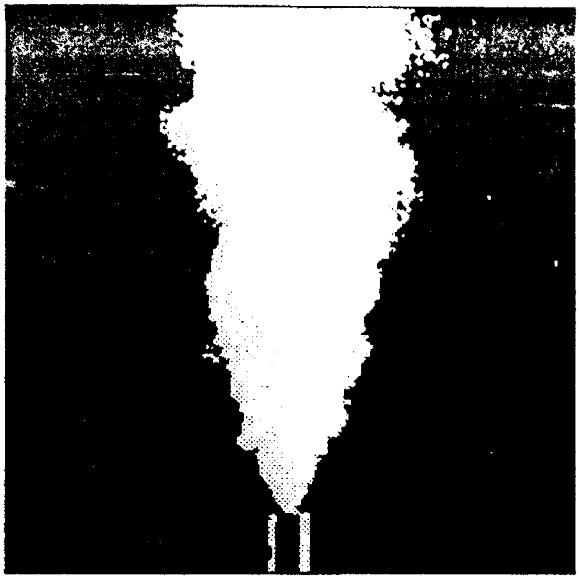

Figure 6. Injection of nitrogen into water with converging/diverging 3:1 slot nozzle. Spreading viewed in minor axis.

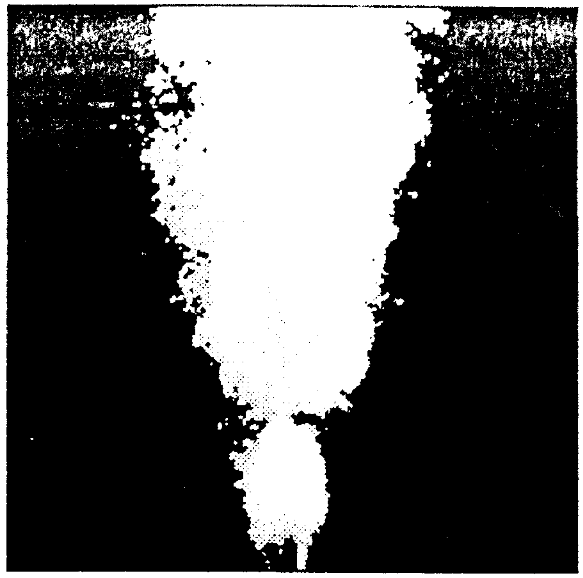

Figure 7. Strobed video frame showing onset of a reverse flow.

The jet spreading angle produced by the Fanno tube is 22° near the nozzle exit. For the 3:1 converging slot the spreading angles are 23° and 26° in the minor and major axes respectively. The 3:1 converging/diverging slot nozzle produced a jet with spreading angles of 40° and 58° in the minor and major axes respectively. In general, converging slot nozzles with no diverging section produce a jet with a slightly larger volume spreading rate than a jet produced by a Fanno tube. While jets produced by a converging slot nozzle which had a diverging elliptical exit showed a large increase in volume spreading rate as seen in the images above. The increase in volume spreading rate for the converging/diverging 3:1 slot nozzle is 3-4 times greater than the volume spreading rate of jets produced by a Fanno tube. The spreading rate of the jets produced by all three types of nozzles is relatively insensitive to the mass flow rate above the choke point.

V. Jet Stabilization

A "reverse shock" instability which causes a large degree of instability in choked submerged jets in liquids was described by Soviet workers[12] in 1983. Here it is referred to as a "reverse flow" effect because it is not certain that a hydrodynamic shock is essential to the effect. The reverse flow phenomenon is characterized by the sudden reversal of a large volume of gas in the opposite direction of the principal flow and back toward the nozzle. Fig. 7 is a strobed video image of the onset of a reverse flow. A large volume of liquid is entrained into the gaseous jet core, blocking the flow of gas and the gas is channeled back towards the injector until the blocking mass of liquid is swept out of the flow path. This phenomenon has been observed in non-reacting as well as reacting systems chosen to model the liquid metal combustion system, and is obviously a potential mechanism for injector erosion, injector plugging and containment failure in intensely reacting and corrosive liquid metal combustion systems. Therefore it is desirable to have a technique for eliminating instability.

Fig. 8 shows the reverse flow frequency as a function of mass flow rate for the three types of nozzles. At lower mass flow rates both non-axisymmetric nozzles showed fewer reverse flows than the axisymmetric nozzle. The frequency of reverse flows for the converging slot nozzle is similar to that of a Fanno tube except that there is a sharp reduction to zero at higher mass flow rates. The converging diverging slot nozzle produced much fewer reverse flows at lower flow rates and a sharply

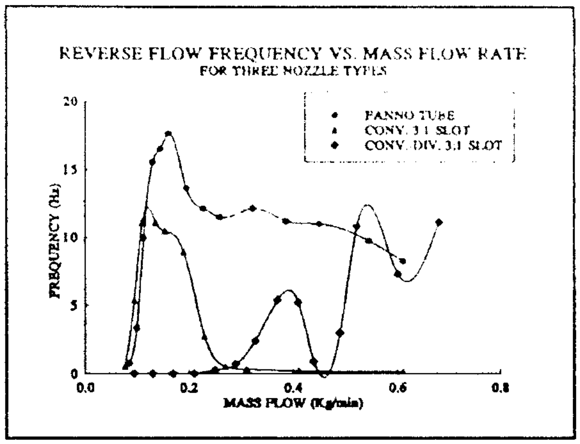

Figure 8. Reverse flow frequency for three nozzle types.

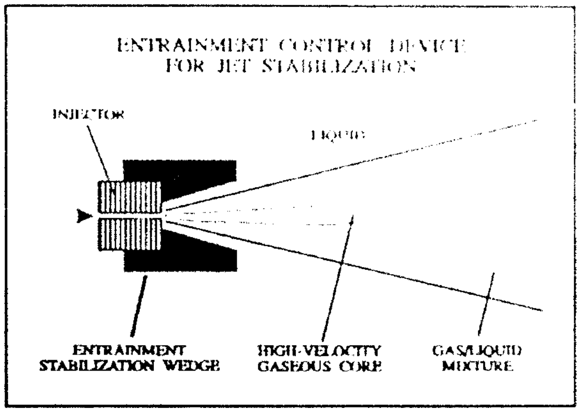

Figure 9. Jet Stabilizer for submerged jets in liquids.

higher number of reverse flows at high flow rates. The converging/diverging slot nozzle produced a dual jet at lower mass flow rates which showed little if any swirl. Jets produced by the Fanno tube and the converging slot produced a single jet with a large amount of swirl about the direction of gas flow. The presence of a large degree of swirl apparently creates the conditions, large turbulent eddy cells, which lead to the lateral perturbations leading to the reverse flow effect. At the point where the converging/diverging nozzle begins to produce significant numbers of reverse flows, about 0.3 Kg/min, the jet begins to switch from the dual jet and to the single jet mode.

It has been found that a simple passive control technique is effective in eliminating the reverse flow instability in the non-reacting nitrogen/water system. The cause of the effect is attributed to lateral flow perturbations on the jets and the development of large scale turbulent eddies which can lead to lateral flow perturbations on the gaseous jet. Therefore by shielding the jet from lateral perturbations and blocking the development of large scale turbulent eddies the reverse flow effect can be eliminated.

Fig. 9 is a schematic of a simple device which can be used to stabilize submerged gaseous jets in liquids. It consists of two planar wedges positioned on opposing sides of the submerged jet and the planes oriented parallel to the spreading angle of the jet. For implementation with nitrogen jets injected into water, planes of length, 2.0 mm, protruding 2 mm past the surface of the nozzle have been found to be effective. Over the range of flow rates studied, 0-1.0 Kg/min, the rate of occurrence of reverse flows is effectively reduced to zero for all three nozzle types. It is somewhat easier to position the device to eliminate reverse flows for the non-axisymmetric nozzles since they are initially more stable than Fanno tube injection. Stabilization appears to be equally effective in the minor plain as in the major plain of the non-axisymmetric nozzles.

VI. Conclusions

Significant enhancement of jet spreading rates was observed with nozzle geometries having a contracting inlet section and an expanding outlet section and an ellipsoidal or slot-shaped gas passage. Jets with increased volume spreading rates of 3-4 times that of jets produced by Fanno tube nozzles were observed. Significantly increased entrainment of liquid into the gas jet is indicated near the nozzle exit.

The structure of submerged jets can be fundamentally altered compared to the structure of jets produced by a Fanno tube. Jets produced by non-axisymmetric nozzles developed a dual jet structure as opposed to the single jet mode produced by a Fanno tube. Volume spreading rate and entrainment were enhanced in the minor and major axes with the greatest increase in volume spreading rate being in the major axis. The non-axisymmetric jets were considerably more stable at relatively low flow rates.

A simple control technique was found to be effective in eliminating a characteristic instability found in non-condensing submerged jets. This technique interrupts the development of large scale turbulence near the nozzle exit and prevents sudden entrainment of liquid into the jet core which results in a reverse flow.

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